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BEAM STUDIES OF SAD-150 HEAVY CRYSTAL PWO CALORIMETER, SMALL ANGLE MULTIPHOTON DETECTOR OF GAMS-4π SPECTROMETER

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Abstract

Binon F.G., Blick A.M., Dolgopolov A.V. et al. Beam studies of SAD-150 heavy crystal PWO calorimeter, small angle multiphoton detector of GAMS-4π spectrometer: IHEP Preprint 97-4. – Protvino, 1997. – p. 11, figs. 7, refs.: 19.

The SAD-150 heavy crystal *PWO* spectrometer, a full scale Small Angle multiphoton high resolution Detector of the GAMS-4π setup, has been built, tuned, calibrated in muon and electron beams, incorporated in the GAMS-4π and successfully tested under conditions of a real high-intensity experiment in 32.5 GeV/c pion beam of the IHEP proton synchrotron. The 90,000 π^os and 10,000 ηs have been recorded. The invariant mass and effective mass resolutions of the SAD-150 in the η meson peak region have been measured to be 2% and 3%, in coincidence with values calculated for this calorimeter with geometry of the experiment taken into account. The SAD-150 showed practically no sensitivity to a high beam load in the GAMS-4π central zone (as large as 10^6 π^-/s through a *PWO* cell).

Аннотация

Бинон Ф.Г., Блик А.М., Донсков С.В. и др. Испытания на пучке SAD-150 – калориметра из тяжелых кристаллов PWO для регистрации фотонов под малыми углами в составе спектрометра ГАМС-4π.: Препринт ИФВЭ 97-4. – Протвино, 1997. – 11 с., 7 рис., библиогр.: 19.

Создан, настроен и откалиброван на электронном и мюонном пучках спектрометр SAD-150 (Small Angle Detector), полномасштабный многофотонный детектор с высоким координатным и энергетическим разрешением, изготовленный из тяжелых кристаллов PWO. SAD-150 включен в состав установки GAMS-4π и успешно испытан в реальном эксперименте на высокоинтенсивном пучке пионов с импульсом 32,5 ГэВ/с, выведенном из протонного синхротрона ИФВЭ. Зарегистрировано 90.000 π^o- и 10.000 η-мезонов. Разрешение по инвариантной и эффективной массе в области η-мезона составляет, соответственно, 2% и 3%, что совпадает с результатами моделирования для этого калориметра с учетом геометрии эксперимента. SAD-150 практически нечувствителен к высокой пучковой загрузке в центральной зоне GAMS-4π (вплоть до 10^6 $\pi^-/сек$ на одну ячейку детектора).

1. Introduction, some of history

In this paper we present the results of beam studies of 155 cell full scale PWO Small Angle Detector, SAD-150 which is destined to detect photons with high energy and space resolution in a heavily loaded central zone of the GAMS-4π spectrometer [1] being used in the experiment on exotic meson studies and glueball search (SERP-E-172). The spectrometer operates in the π^- beam of the 70 GeV IHEP accelerator.

Previously, SAD-60, the SAD-150 prototype, has been beam tested [2], the results being used in building the SAD-150 final version. During the November-December 1996 run, the SAD-150 has been assembled, tuned, calibrated in 20 GeV/c muon and 9.3 GeV/c electron beams, incorporated in the GAMS-4π setup and successfully tested in the 32.5 GeV/c pion beam.

With the SAD-150, the first PWO spectrometer capable of detecting neutral mesons decaying into high-energy photons, now in operation, a four-year extensive R&D programme of PWO calorimeter studies has been completed. The programme started with the laboratory producion of first calorimeter-size PWO crystals and initial beam tests of crystal matrices [3,4] (IHEP-INP collaboration, with LAPP and KEK groups joined later). Further successful beam tests (1993-1994) of the first full scale PWO calorimeter prototypes at IHEP and CERN accelerators [5-9] allowed the ALICE collaboration [10] and then the CMS collaboration [11] to make their PWO choice (instead of CeF_3, "shashlik", etc.). Recent electron beam tests of the PWO matrix made of CMS ECAL barrel-type tappered cells [12] confirmed our earlier results.

2. The SAD-150 PWO calorimeter

The SAD-150 is the 13×12 matrix composed of 22 X_o to 26 X_o long PWO crystal cells. The cells are hexagonal prisms with the width of 24 mm, viewed from the rear end by 3/4" photomultiplier (PMT), detecting the scintillation light. 40 central SAD-150 cells are equipped with Philips XP1911 PMTs, for other cells the FEU-147 PMTs are used.

Unlike the SAD-60 [2], which was built of *PWO* crystal cells produced at the Bogoroditsk Techno-Chemical Plant (Tula, Russia) with cheap 1995 mass production technology using medium-purity raw materials (these crystals show an essential slow component [13]), in the central SAD-150 region, around one-cell hole, 20 *PWO* cells produced with new 1996 technology are used (the *PbO* and WO_3 being purified of any contamination to $< 2 \cdot 10^{-6}$ level including the *Mo* element responsible for slow (microseconds) component in the *PWO* scintillation kinetics). The new technology provides by an order of magnitude smaller slow "tail" [13].

The *PWO* scintillation light yield is sensitive to temperature variations ($-1.9\%/^oC$ [9]). Thermal stabilization is provided with an air flow through the SAD-150 box. The *PWO* temperature has been monitored with 0.1^oC precision and written on a tape during the whole run to correct the data off-line. The slow temperature daily variations amounted to $\pm\, 0.6^oC$, being followed rather precisely by the SAD-150 signals (fig. 1) with ratio

$$\Delta(\text{Light yield})/\Delta(\text{temperature}) = -(2.1 \pm 0.2)\%/^oC$$

as measured in the present work.

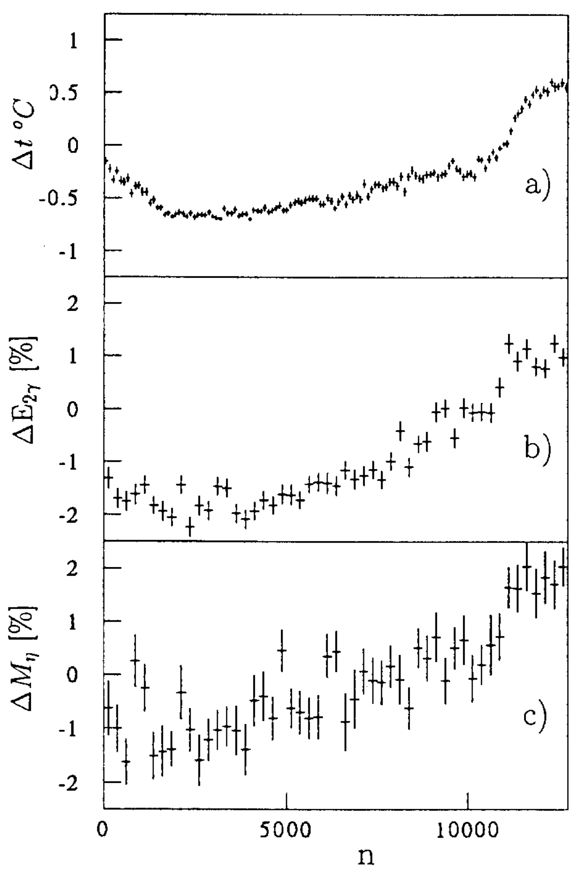

Fig. 1. Correlation between SAD-150 signals (2γ energy peak (b) and η peak (c) positions) and the *PWO* cell temperature (a) during a 36 hours π^- run; n is the number of accelerator bursts (8,000 per day).

In the SAD-150 study we have used an upgraded DAQ system of the GAMS-4π spectrometer. An extra double EURO crate with 12 bit QDCs integrating the *PWO* signals over 60 *ns* gate has been incorporated into the existing GAMS-4π DAQ system. A detailed description of the amplitude analysis system is given elsewhere [14]. The data acquisition is controlled by FIC8232 single board Motorola MC68030 based computer placed in the VME crate. One Mbyte triple port high speed memory HSM-8170 was used as an event spill buffer. An overall control is performed by the CETIA workstation interconnected by VIC8250 to the VME crate. Information from all GAMS-4π detectors is written on tape together with that of SAD-150. The DAQ performance is up to 2000 events per second depending on the event size.

For more details on SAD and its monitoring system, see [2].

3. Beam calibration of the SAD-150

A wide ($\approx 1\ m^2$) muon beam of 20 GeV/c momentum has been used to calibrate the SAD-150 along with other large GAMS-4π detectors. To increase the muon trigger efficiency for the SAD-150, a $20 \times 20\ cm^2$ plastic scintillation counter is put in front of it. The typical muon spectrum measured in a *PWO* cell during calibration is shown in fig. 2. The muon signal is very small, it lies just at the beginning of our dynamical range. Nevertheless, the muon calibration is already good enough to fix the SAD-150 channel gains (within 10%), thanks to excellent dynamical linearity of our 12 bit QDCs.

The calibration of SAD-150 performed in 9.3 GeV/c electron beam has given the results similar to [2]. The calibration coefficients (the electron peak position, fig. 2) are set in each channel with a precision of 0.3%. The electron spectrum is as narrow as $\sigma_E/E = 2.6\%$ in the best cells (by 20% better than in SAD-60 [2]). This value, after correction for electron beam momentum spread (2%), agrees well with the SAD-150 intrinsic resolution that, according to the beam measurements [9,15] and Monte Carlo calculations [16], should be:

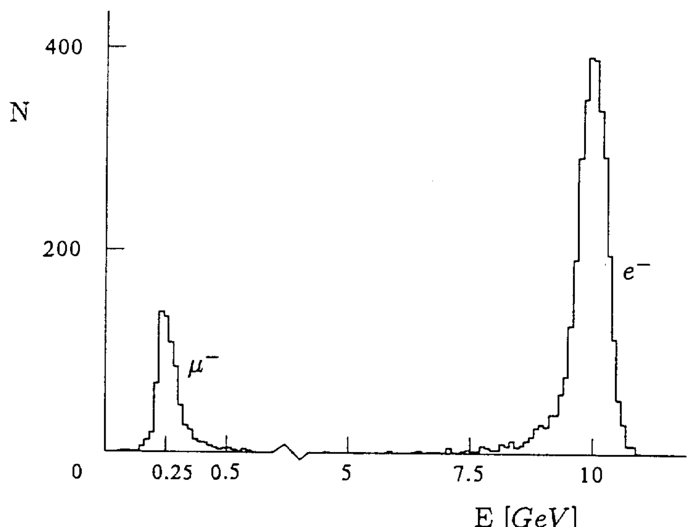

Fig. 2. Muon and electron spectra measured in *PWO* cells during the SAD-150 calibrations.

$$\sigma_E/E = 3.5\%/\sqrt{E} + 0.4\%. \tag{1}$$

However, not all the 155 crystals and PMTs of SAD-150 are perfect, for the whole matrix $\sigma_E/E = 3.0\%$. For more details of the SAD-150 calibration procedures, see [2].

All other GAMS-4π detectors have been beam calibrated in a standard GAMS manner (see [14,17], as well as [18], for refs.).

4. Measurements of charge exchange events, SAD-150 off-line fine tuning using π^o and η signals

With the SAD-150 precisely calibrated (cell-to-cell electron peak position did not vary more than by 0.5% over the whole *PWO* matrix surface), the beam line was switched to 32.5 GeV/c π^- mode. The scheme of the setup used in π^- beam measurements is presented in fig. 3.

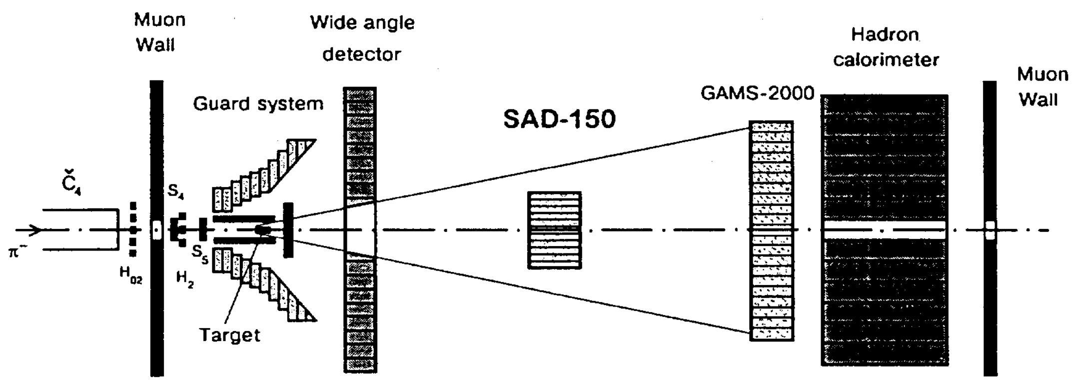

Fig. 3. The setup scheme of the SAD-150 beam tests using the GAMS-4π spectrometer. For details of the spectrometer see [1].

The π^- beam spot (≈ 5 *cm* in diameter) being much larger than the SAD-150 central hole, a large fraction of the beam hits the *PWO* cells around the hole. This reproduces experimental conditions typical for future high luminosity experiments, and allows one to test the SAD-150 under such conditions.

The standard GAMS trigger [17] selects neutral meson states, produced in the charge exchange reaction

$$\pi^- p \;\rightarrow\; M^o n, \qquad M^o \hookrightarrow k\gamma \tag{2}$$

5 *cm* long CH being used as a target.

The measurements have been performed at two target to SAD-150 distances: 3.8 *m* and 5.5 *m*. The major amount of data has been collected at smaller distance, where the SAD-150 was able to detect with high efficiency both the π^o decay

$$\pi^o \rightarrow 2\gamma \tag{3}$$

(with poor mass resolution due to a strong shower overlapping), and the η decay

$$\eta \rightarrow 2\gamma. \tag{4}$$

Both the π^o and η signals have been used off-line for "self-calibration" [2] of the SAD-150.

Two beam intensities have been used: $5 \cdot 10^6$ π^-/s and $1.5 \cdot 10^6$ π^-/s (as measured with a 2.5 cm diameter S_5 beam counter). A short run was performed at 5.5 m distance to collect π^o data (in this case the η decay (4) is practically outside the SAD-150 aperture, see fig. 4[1]). During the π^- beam data taking, $4 \cdot 10^6$ neutral trigger events have been written on tape, with a total flux of $3 \cdot 10^{10}$ π^- through the target. These events are further processed with the gamma shower reconstruction programs.

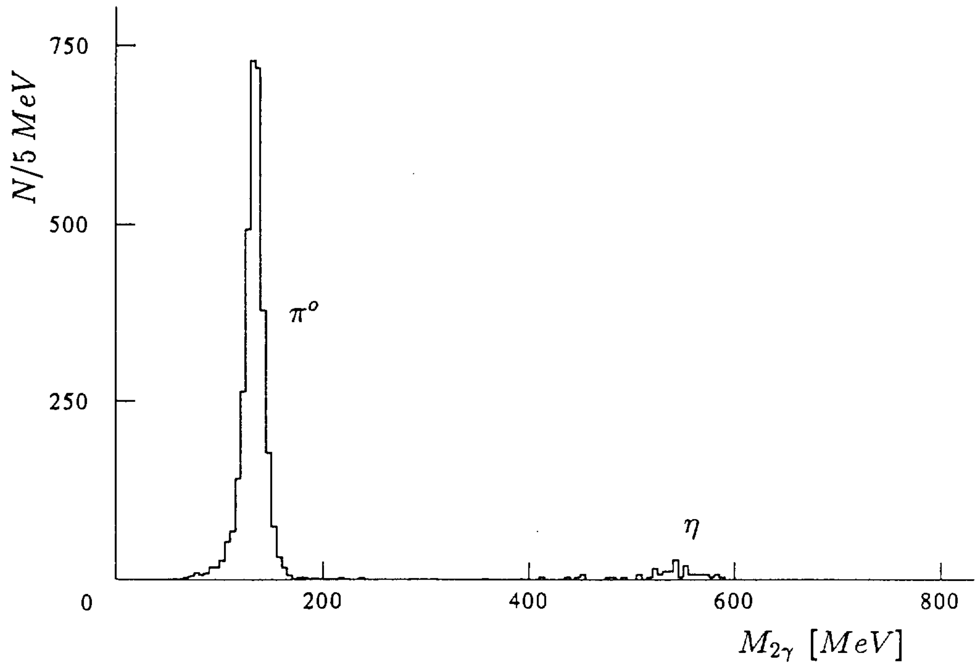

Fig. 4. Effective mass spectrum of gamma pairs measured at a large distance, $L = 5.5$ m.

5. Pile-up effects

The procedure of measuring the pile-up effects with pedestal events triggered inside the accelerator beam spill is similar to that of [2]. Fig. 5 shows the energy spectra deposited in such events in two cells: one is near the matrix hole (up to 10^6 π^-/s beam load), the other is chosen in the second row of the matrix, where the beam load is by an order of magnitude lower. There are no pile-up effects above 50 MeV visible in the first cell (the 1996 *PWO* production technology [13]) both at low and high beam intensities. The picture is drastically different in the case of SAD-60 [2] ("slow" crystals, the 1995 *PWO* production technology [13]). Here the threshold well above 1 GeV should be imposed.

[1]Here and further, in the mass spectra, the events in η region are shown multiplied by 4.

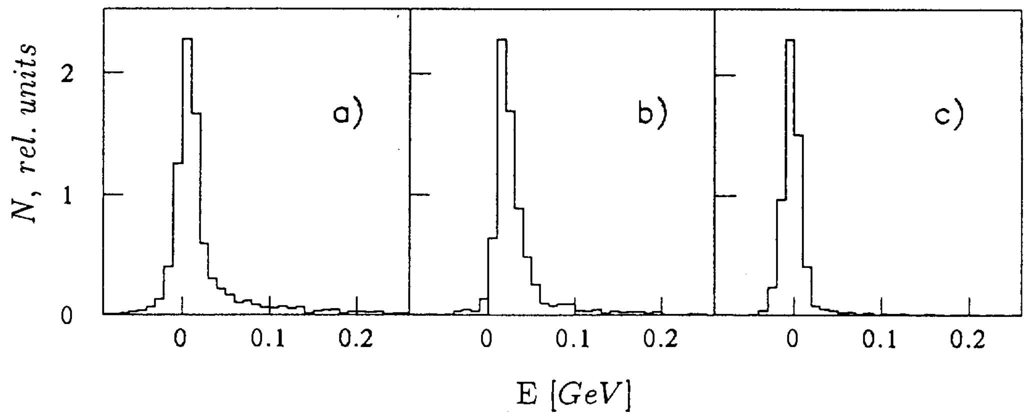

Fig. 5.1. Pile-up effects in *PWO* cells of the SAD-150. Energy spectra measured with pedestal events during accelerator bursts. The cell is close to the matrix hole, high intensity (a), and low intensity (c) of the pion beam; the cell is from second matrix row, high intensity (b).

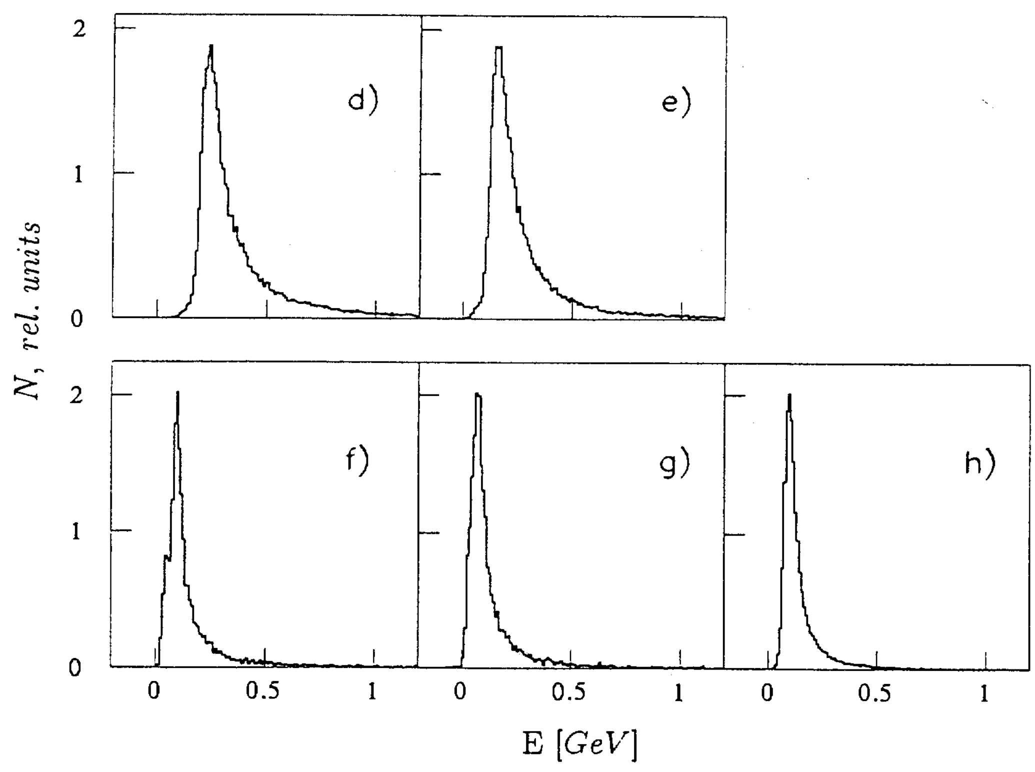

Fig. 5.2. The same as in fig. 5.1, but for SAD-60. d: the same as a) in 5.1; e: the same as b); f: the same as d), but low intensity; g: the same as e), but low intensity; h: the 3rd row cell, high intensity.

6. Event reconstruction

In the described measurements only the two-gamma events are of interest, therefore a simplified algorithm is used in the event kinematical reconstruction. First, the clusters of fired cells are selected. Then each cluster is studied in a search for peaks, i.e. cells with energy deposit higher than in the neighbouring cells. Under assumption that the number of photons in a cluster is equal to the number of discovered peaks the cluster is processed with the fitting program used to determine the photon coordinates and energies.

The fitting program searches for a minimum of the functional

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{A_i - \sum_{j=1}^{q} E_i^j(x_j, y_j, e_j)}{aA_i + b} \right)^2 \qquad (5)$$

under the $\sum_{j=1}^{q} e_j = E_{cl}$ constraint. Here A_i is the measured energy deposited in the i-th cell, E_i^j is the energy deposited in the same cell by the j-th photon with energy e_j, hitting the SAD-150 at x_j, y_j; q stands for the number of photons in the cluster, N is the number of cells in the cluster, E_{cl} is the total energy of the cluster, and a and b are empirical constants.

E_i^j is calculated by integrating the 2-d lateral shower shape within the region occupied by the i-th cell. The shower shape in PWO crystals has been determined using the data obtained with the PWO matrix of square cells irradiated by 10 GeV electrons using the procedure described elsewhere [19].

The χ^2 value is then used as a criterion of the validity of the hypothesis chosen. In case of a low probability of the accepted hypothesis, the number of photons q in a cluster is increased by one and the fitting procedure is repeated. If q exceeds two, the event is rejected.

7. Invariant mass spectra

The energy spectrum of 2γ events taken from the η mass region has a shape of a narrow peak with $\sigma_{E_{2\gamma}}/E_{2\gamma} = 1.5\%$. This gives the evidence that we are dealing with ηs predominantly produced in the exclusive reaction (2), (4), the admixture of inelastic processes being small. Then one may put a constraint: all particle masses in reaction (2), except M^o, being fixed on their table value.

The 1C fit invariant mass spectra of 2γ events, M_{inv}, are shown in fig. 6[2]. The M_{inv} practically does not depend on the SAD-150 energy resolution (1), the mass resolution is expressed as:

[2]To select pure 2γ events from those of higher multiplicity, here and further on in the mass spectra the GAMS-2000 signal is used off-line in veto with the threshold requirements $E_{GAMS} > 5$ GeV. There is no loss in η events due to this selection. Without GAMS-2000 in veto the background between π^o and η peaks would be two orders of magnitude larger. The 2γ events are also selected according to the decay symmetry: $cos\theta_\gamma < 0.35$, where θ_γ is the decay angle in the c.m.s. of $M^o \to 2\gamma$.

$$\sigma_{M_{inv}}/M_{inv} = (\sigma_{r_{\gamma\gamma}}/r_{\gamma\gamma} \oplus l_T/2L \oplus K_{xt}) \oplus \sigma_{p_{\pi^-}}/p_{\pi^-}, \quad (6)$$

where $r_{\gamma\gamma}$ is the space separation of two showers produced by photons in the SAD-150, l_T is a correction due to the GAMS target thickness (0.7% at L = 3.8 m), L is the target-to-SAD distance, K_{xt} is the SAD-150 channel cross-talk averaged over the PWO matrix (0.5%). The last entry in (6) is the π^- beam momentum spread (1.2%).

As is seen in fig. 6a, the invariant mass resolution for ηs is quite good, 1.9%. There is no change in the η peak with the intensity increase (fig. 6b).

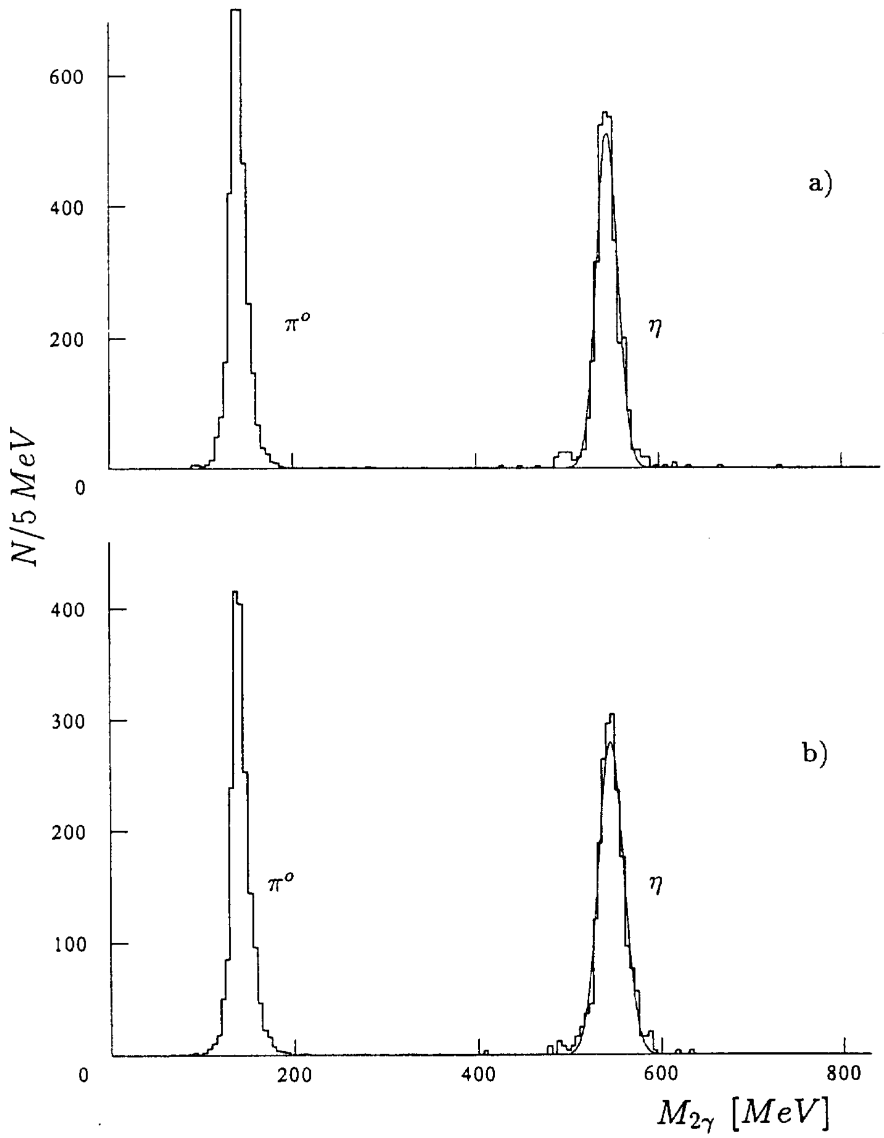

Fig. 6. Invariant 2 γ mass spectra measured at a small (3.8 m) distance, with low (a) and high (b) pion beam intensity.

8. Effective mass resolution

At high energies, for inclusively produced light mesons decaying through 2γ channel, the effective mass resolution of the SAD-150 is defined both by the energy and space resolutions of gammas:

$$\sigma_{M_{eff}}/M_{eff} = (\sigma_{E_{\gamma 1}}/E_{\gamma 1} \oplus \sigma_{E_{\gamma 2}}/E_{\gamma 2})/\sqrt{2} \oplus \sigma_{r_{\gamma\gamma}}/r_{\gamma\gamma}. \quad (7)$$

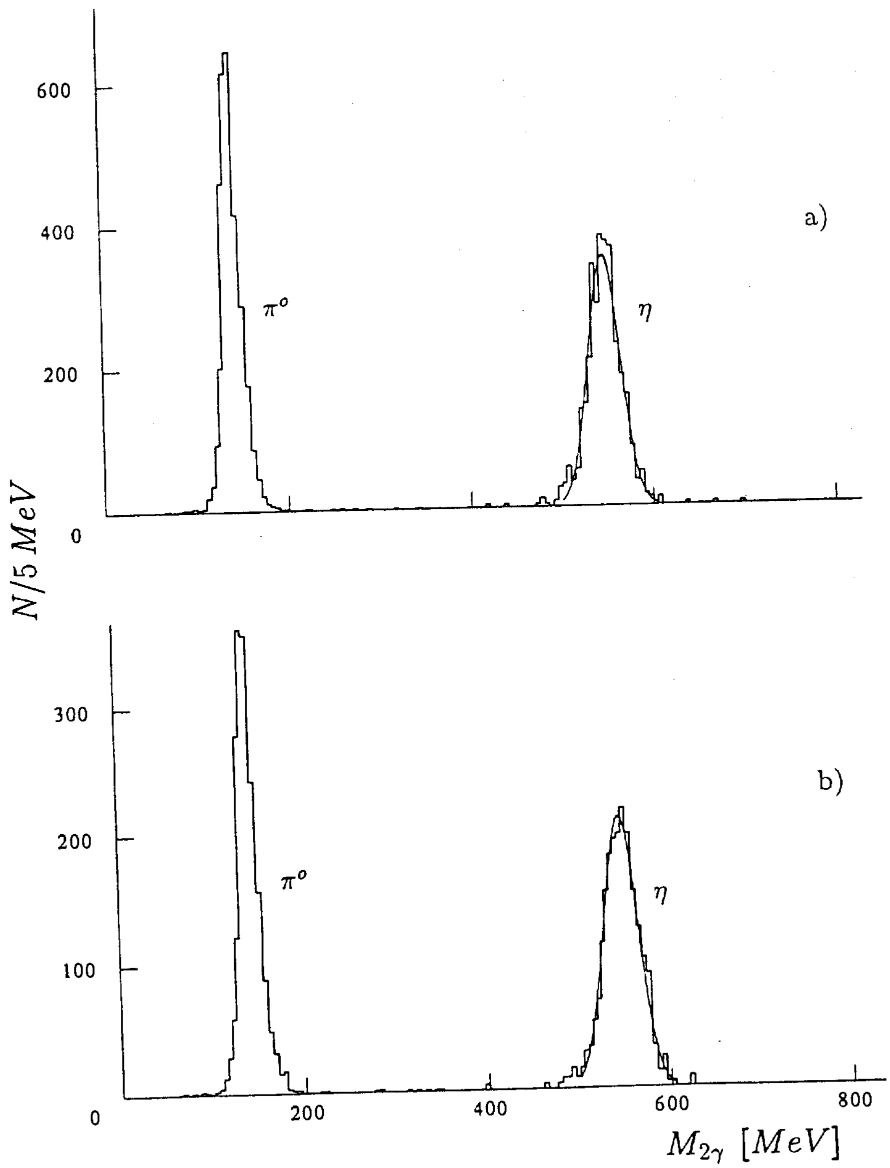

Fig. 7. The same as in fig. 6, but for the effective gamma-pair mass spectra.

Fig. 7a shows the effective mass spectrum of gamma-pairs measured at a small distance (3.8 m) and low π^- beam intensity. Effective mass resolution measured for the η peak equals 2.9%. Estimate (7) gives 2.6% for this value.

With the beam intensity increasing, the η peak widens by 7% (fig. 7b). This is the result of inhomogeneous SAD-150 structure: the gammas from $\eta \to 2\gamma$ decay are concentrated on the SAD-150 periphery, but that part of the detector is built of slow, rate sensitive PWO crystals. Contrary to this, there is no change in π^o peak with beam intensity: $\pi^o \to 2\gamma$ are concentrated in the central SAD-150 zone built of fast PWO crystals.

With its Moliere radius as small as 2 cm, the PWO calorimeter allows one to reliably distinguish two-shower events from single-shower events even when showers are separated by 1 cm. Fig. 7 illustrates this remarkable feature of PWO : the π^os are quite well reconstructed while the two gammas are 3.5 cm apart only hitting two neighbouring cells of SAD-150.

Conclusions

The SAD-150 heavy crystal PWO spectrometer, a full scale Small Angle multiphoton high energy and coordinate resolution Detector of the GAMS-4π setup, has been built at IHEP, tuned, calibrated in muon and electron beams, incorporated in the GAMS-4π and successfully tested under conditions of a real high-intensity experiment in a 32.5 GeV/c pion beam of the IHEP proton synchrotron. The effective and invariant mass resolutions of the SAD-150 in the η-meson peak region are measured to be 3% and 2%. These values agree with those calculated with account of the parameters of the experiment. The SAD-150 shows practically no sensitivity to a high beam load in the GAMS-4π central zone (as large as 10^6 π^-/s through a PWO cell). With the SAD-150 in operation, a long-term programme of the GAMS-4π upgrade has been completed. This is also an important milestone in the PWO calorimetry R&D programme of CMS and COMPASS projects.

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